WATERSHED MANAGEMENT RESEARCH IN THE SOUTHWEST

(A Literature Review)

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Settlement began early in the Southwest. Spanish missions were established in southern Arizona in the 17th Century.

From the beginning the settlers in this arid section of the Nation of necessity were water conscious. Almost everything they did had to be geared to the available water supplies. The rise and fall of the earlier Indian cultures also appear to have been related to the then existing water supplies.

As more settlers came and communities grew and lands began to be farmed, water became even more important. The first water was diverted from the Salt River in 1869. In 1875, as diversions increased in number and complexity, a storage dam was proposed. Passage of the Reclamation Act in 1902 made federal funds available for this purpose. By 1902 the Salt River Valley Water Users' Association was organized, and construction of Roosevelt Dam was started in 1905 (Salt River Project, 1954). This dam, plus later additions, gave residents of the valley assurance that the available streamflow and flood runoff would be saved for irrigation.

About this same time attention was directed to the need for the protection of the upstream watersheds. Watershed protection was one of the main purposes in establishing the Tonto National Forest in central Arizona in 1904.

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Many observations concerning streamflow and the use of water have been made over the years by farmers, ranchers, miners, land managers, and others. Unfortunately, few of these early observations and experiences were recorded. However, there are some general accounts of settlement. Horgan's treatise (1954) of the Rio Grande is a good example.

Watershed management research in the Southwest had its start with the observations of early workers in forestry and range management research. Much of their observations is not available to the literature. Yet, these early workers planted the seed of watershed research. One of these early workers was Carlos G. Bates, whose research in silvics at the Fremont Station west of Colorado Springs, Colorado, included appraisals of tree physiology, water use and the relation of vegetation to climate (Bates, 1923 and 1924). On June 1, 1910, under Raphael Zon's guidance (Zon, 1912) and in cooperation with the U. S. Weather Bureau, Carlos Bates and co-workers initiated the first field work at Wagon Wheel Gap, Colorado. The results of this study represents the first watershed test in the Southwest and in the United States. As Bates and Henry (1922) stated in their first report, the objective of this study was to "bring out faithfully and clearly the effects upon streamflow and erosion which are produced by denudation of one of the watersheds."

During the years since the start of the Wagon Wheel Gap study and until recently, work in watershed research in the Southwest has been limited and sporadic. Studies began in the 1930's with emergency funds were helpful in laying the groundwork for the recent accelerated watershed research programs.

Practically all of the early studies in watershed management research were designed to evaluate the protective value of forests and rangelands against soil erosion and floods. Only recently has research been designed toward determining how to safely increase water yield through alteration and changes in vegetation. This has been brought about by the great need for additional water supplies in an attempt to keep pace with the rapid expansion in the Southwest.

For the purpose of this literature review, the Southwest includes Arizona, New Mexico, and adjacent areas in Texas, Colorado, Utah, and California. Some research completed elsewhere that bears on the water problem in the Southwest is also included. Also, the scope is limited mostly to pertinent findings that are published and readily available.

Although much research remains to be done in the Southwest to devise sound and economical ways of obtaining maximum values from watersheds, still much has been accomplished. These research findings may be classified into three categories somewhat comparable to those described by Colman (1953):

1. Studies to develop a better understanding of hydrologic processes, the so-called basic researches. These include studies of climate and soil, and the quantities and processes involved in infiltration, interception, transpiration, and evaporation.

2. Studies to evaluate watershed improvement practices on soil stability and water yield. These include the effects of various degrees and intensities of livestock grazing, the effects of fire, and timber harvesting.

3. Studies of vegetation changes made primarily to increase water yield, sometimes without regard for maximum production of wood, forage, and other values. These include snow-pack studies, studies to reduce evapo-transpiration on watershed lands through changes in vegetation cover, and studies to control riparian water losses.

HYDROLOGIC PROCESSES

Vegetation influences in many ways the various hydrologic processes through which water passes from clouds to its place of use. Colman (1953) classifies these processes as those concerned with, (1) falling rain and snow (interception); (2) snow accumulation, evaporation and sublimation, and melt; and (3) water in transit involving infiltration, storage and drainage, evaporation and transpiration, and surface flow and sediment load including erosion and deposition.

Nichol (1937), Hunter et al., (1939), and Little (1950), divide the vegetation of the Southwest into seven major groups: (1) High altitude forest composed of fir, spruce and pine mingled with some aspen groves; (2) ponderosa pine forests; (3) pinyon-juniper woodland; (4) chaparral; (5) grassland; (6) desert shrub; (7) riparian vegetation.

McGinnies (1952) summarizes, through a literature review, the ecology of arid and semi-arid areas including plant communities, soils, and climate.

CLIMATE

The general pattern of climate in the Southwest has been fairly well determined. Measurement of rainfall started by 1865 at the early Army Posts (Smith, 1956). In 1903, measurements were started on the forested watershed areas (Pearson, 1931). Using these long-term records, McDonald (1956) analyzed the variability occurring in Arizona. Studies of tree rings by Schulman (1945, 1946, 1948, 1949) and Antevs (1938) present regional and local chronology for parts of Arizona and adjacent surrounding territory. Dorroh (1946) presents certain hydrologic and climatic characteristics of the Southwest and includes descriptions of storm types, quantity and distribution and precipitation, and storm intensities as they are related to runoff from rainfall and melting snow. Leopold (1942, 1944) presents aerial extent and characteristics of intense and heavy rainfall in New Mexico and Arizona, and discusses storm types affecting the Southwest. Harrold (1943) discusses thunder storms and runoff at high elevations in northwestern New Mexico at the Navajo Experiment Station. Recently, Bryson (1957) analyzed the annual march of precipitation in Arizona, New Mexico, and northwestern Mexico.

Russler and Spreen (1947) analyzed the topographic influences on mean annual and mean winter precipitation in adjacent areas of western Colorado, showing that elevation, rise, exposure, orientation, and zone of environment accounted for 85 percent of variation in precipitation. Measurements of rainfall on mountain watersheds where topographic effects are sharp require special instrumentation. Progress on many of these problems has been reported by Hamilton (1954).

Recently, the University of Arizona established the Institute of Atmospheric Physics for basic research in the study of weather and its control (Kassander, 1957). Reitan (1957) has studied the role of precipital water vapor in Arizona summer rains. He found that occurrence of rain was primarily determined by the moisture content of the air over the State.

Although general climatic information is available, there is need for additional data regarding patterns and behavior of specific climatic factors, especially on the higher watershed areas where streamflow originates. Data on microclimate are especially needed to relate to hydrologic processes.

INTERCEPTION

Vegetation intercepts rain and snow before they reach the earth's surface. Several studies have been made regarding the interception losses by various plant groups. Significant to the Southwest are the studies made by Rowe and Hendrix (1951) in a pine forest near Bass Lake, California. These workers found that approximately 12 percent of the total annual precipitation was lost by interception from a 70-year old stand of ponderosa pine.

Cable (1958) related tree diameter to foliage surface area to aid in analyzing interception losses. In a mixed pine-fir forest stand in central Arizona, he also found that interception loss could be correlated to densities. Interception of precipitation in the most dense stand (209 sq. ft. basal area per acre) accounted for 22.41 percent of summer precipitation and 14.41 percent of winter precipitation. In an open stand (64 sq. ft. basal area per acre) interception accounted for 4.58 percent of the precipitation in summer and 3.4 percent in winter (unpublished manuscript).

Johnson (1942) reporting interception studies on three small watersheds at the Manitou Experimental Forest in Colorado showed that approximately 17.5 percent of the rainfall during the period studied was intercepted by pine trees.

In studying interception losses Wilm (1946) outlined the principles and use of a method for sampling amount of rain reaching the ground under a forest canopy during a series of storms. Dunford and Niederhof (1944), working near Fraser, Colorado, reported less water in the snow pack and less precipitation reaching the ground under a dense stand of lodgepole pine than in aspen and grassland.

Forest litter also affects precipitation before it reaches the soil. Rowe (1955) reported that evaporation from a ponderosa pine forest floor 1 inch deep averaged 3 percent of the annual precipitation. For a 2.7-inch floor, it was 4.6 percent; and for a 3.6-inch floor, 5.3 percent.

Chaparral cover apparently intercepts less precipitation than forests. Hamilton and Rowe (1949) reported that approximately 11 percent of the annual precipitation in a dense chaparral cover in southern California would be lost. Only 5 percent loss was measured in a partly deciduous brush stand near Northfork, California.

SNOW

Vegetation affects both snow accumulation and melt. Part of the snow falling in a forested area collects on the canopy and is lost by evaporation. Kittredge (1953) found average seasonal snowfall losses varied from 13 to 27 percent in stands of sugar pine and ponderosa pine in California. In a dense white fir stand in California, snowmelt was about one-half as rapid as that in a large clearing. Similar effects of forest cover on snow have been reported by Jaenicke and Foerster (1915) in Arizona, Anderson (1956) in California, and Goodell (1952) in Colorado. Miller (1956) describes the influence of a pine forest in the Sierra Nevada on the heat transmitted to a snow pack. The heat given off from the trees to the air is sufficient to heat the surface layer, supply direct heat to the snow, and provide for a small loss aloft. Garstka et al., (1958) summarized snow data collected at the Fraser Experimental Forest in Colorado. They present the various factors affecting snowmelt and streamflow. Brown and Dunford (1956), also reporting work at Fraser, show the possibility of predicting peak streamflow from the amount of area bare of snow on the watershed.

The results of these studies, although based on data collected from small plots, suggests strongly that forested watershed lands having snow pack could be managed to increase the amount of total water yield (Wilm and Dunford, 1948). Federal-State cooperative snow surveys reporting snow cover for specific locations are available. The report for Arizona by Anderson and White (1953) is an example.

INFILTRATION

Infiltration or the rate of water entry into the soil is a most important phase of the hydrologic cycle in the Southwest. In this arid and semi-arid region where soil and vegetation are in delicate balance, any change from subsurface to surface flow might have disastrous effects on downstream lands. A fundamental knowledge of infiltration including quantities involved is essential in application of any program of watershed treatment.

Development of the infiltrometer (Rowe, 1940, Dortignac, 1951), a rainfall simulator, has greatly facilitated the measurement of water absorption under varying conditions of soil, vegetation, and land use. Smith and Leopold (1942) found infiltration to be correlated with soil characteristics and the amount of vegetal cover in the pinyon-juniper, grassland, and creosote bush types in the Pecos River drainage. Woodward (1943) obtained similar results in the Sevier Lake watershed in south-central Utah. Infiltration rates increased with increasing plant cover within each vegetation and geologic class. Grazing has been found to influence infiltration rates in pine-grass stands or in mixed woodland and forest types. Deteriorated rangelands have lower infiltration rates than ranges supporting a good stand of perennial grasses (Turner and Dortignac, 1954). Heavy grazing affects infiltration by reducing the amount of vegetation and litter covering the ground, as well as compacting the surface soil by trampling (Packer, 1951, Dortignac, 1958). Johnson (1938), reporting infiltration and capillary rise in sandy soils, compared the hydrologic characteristics of soils derived from granite in Colorado with glacial soil from Minnesota.

EVAPO-TRANSPIRATION

The amount of evapo-transpiration loss depends upon plant type and species, rooting depth, soil, and available moisture. Shantz (1948) presents the basic concepts concerning the water economy of plants. Lassen et al., (1952) discuss available technical knowledge regarding the more important natural principles that govern the interrelations of plants, soil, and water. Blaney (1958) presents data on consumptive use (evapo-transpiration) by natural vegetation and indicates how this information may be used in determining consumptive-use requirements in river basins.

Methods of evaluating evapo-transpiration losses have varied from the direct measurement of losses from individual plants to determination of losses from an entire watershed. Other methods have included measurements of soil moisture losses, use of various-sized lysimeters, and gaging of stream sections. Recently, an apparatus utilizing an infrared-gas analyzer for measurement of vapor changes has been used (Decker and Wetzel, 1957). Transpiration of leaves or small branches (Decker and Wien, 1958), or evapo-transpiration rates for shrubs up to 8 feet in height can be measured.

At Pine Flat near Albuquerque, New Mexico, soil moisture under pinyon pine and blue grama grass has been studied by the Forest Service since 1952. This study indicates that replacement of pinyon trees with herbaceous vegetation cannot be expected to increase water yield except during years with above-average winter precipitation when it penetrates to bedrock at 30 inches (Dortignac, 1956a).

Roeser (1940) determined the relative water utilization and efficiency of some Rocky Mountain conifers in central Colorado. Based

on magnitude of water loss, the species tested were ranked as follows: Englemann spruce, Douglas fir, pinyon pine, ponderosa pine, and limber pine. In relative efficiency of use of water in production of organic matter, the species ranked as follows: Pinyon pine, Douglas fir, Engelmann spruce, ponderosa pine (when grown on loam), and pinyon pine and limber pine (in Permian red sand).

At the Sierra Ancha Experimental Forest in central Arizona from 1936-1939 water use of several plants was determined from lysimeters. Perennial grasses grown in lysimeters under natural rainfall at an elevation of 2,500 feet used 92 percent of the precipitation, winter annuals used 98 percent, and 89 percent of the precipitation was lost from bare soil by evaporation (Rich, 1952). At an elevation of 5,100 feet comparative water use was 81 percent of the precipitation for grasses, 84 percent for evergreen shrubs, and 78 percent loss from bare soil.

McGinnies and Arnold (1939) in studying water requirements of Arizona range plants found that summer annuals used the least water, xerophytic trees and shrubs used the most water, and perennial grasses were intermediate. Love (1934) examined the osmotic values of native forage plants under different climatic and soil conditions in southern Arizona.

Watersheds in the mixed grassland-chaparral zone (elevation 3,800 feet) in central Arizona have evapo-transpiration losses ranging from 94 percent to 98 percent of precipitation; grassland-chaparral watersheds (4,500-4,900 feet), from 90 percent to 95 percent; forested watersheds (elevation 5,500-7,800 feet), from 77 percent to 90 percent, depending on depth of soil and slope (Rich, 1952).

Consumptive use during the summer period was about the same as precipitation and was related to the moisture available. Little or no water other than surface runoff was yielded to streamflow during the summer. Water use during the winter depended on growing conditions. Surplus water first satisfied the soil-moisture deficit and the balance was yielded as streamflow. Type of vegetation cover and its consumptive use in the spring growing season is believed to affect the amount of water yielded (Rich, 1952).

Sierra Ancha studies have been verified from results of the San Dimas lysimeters in southern California (Colman and Hamilton, 1947). Woody species utilized all available moisture during the long, dry summer characteristic of that climate. Grass did not use appreciable moisture below 3 or 4 feet. During the winter season, pine and grass utilized the water more rapidly than the scrub oak. In the years before the lysimeters were planted to woody species, they were sown to annual grass, which gradually changed to a grass-forb cover. While the soil-water loss under the annual grass did not extend below 4 feet of soil, the water in the lower soil layers was depleted when the stand of summer-growing forbs appeared (Colman, 1953).

Grass density affects yield of water as shown by other lysimeter studies on the Sierra Ancha Experimental Forest (Martin and Rich, 1948). The lysimeters were so constructed as to measure the surface runoff and the subsurface flows. In the calibration period from 1935 to 1942, surface and subsurface flows were similar between the three untreated lysimeters. During the period 1942 to 1948 one lysimeter was left as a control; grass density on another was reduced by heavy grazing and on a third by moderate grazing. Winter water yield was not affected by grass density reduction. During intense summer storms surface flow increased as cover decreased. The high density lysimeter yielded 1.8 percent of the rain as surface flow; the moderate density lysimeter, 5.5 percent; and the light density lysimeter, 10.8 percent. None of the summer rains penetrated deeply enough to affect subsurface flows. Increased surface flow during summer storms markedly increased erosion, nullifying benefits derived by the increased water.

In the Thurber fescue grasslands and associated stands of aspen and spruce in western Colorado the following preliminary relative water-uses were obtained: Mixed grass-weed, 9.34 inches; Thurber fescue, 9.86 inches; Idaho fescue, 10.14 inches; spruce, 15.30 and 13.70 inches; and aspen, 20.94 and 17.14 inches (unpublished manuscript).

Water evaporation from large reservoirs and lakes is an important loss in our available water supply. Beadle (1956) reporting recent advances in evaporation control on storage reservoirs estimated annual losses to vary from almost 1 million acre-feet in New Mexico to more than 18 million acre-feet in Texas. He suggested losses of water by evaporation can be retarded in several ways: Monomolecular film applied to water surface; construction of reservoirs with maximum average depth; concentration of water into single reservoirs; elimination of marine growth; elimination of shallow water areas; storing water in ground water reservoirs-recharge underground; reservoir roofs, floating covers, and sealants; and windbreaks. Long straight-chain primary compounds show the most promise as evaporation retardants. Hexadecanol and octodecanol appear suitable. Retardants have shown savings in evaporation of 93 percent for short periods of time to 45-50 percent for as long as 15 days in the laboratory and 5-8 days in the field. The main problem is in developing a practical and economic method for reservoir evaporation control.

Streamflow in coastal California streams shows marked daily losses by riparian vegetation (Taylor and Nickle, 1933). A major study of phreatophyte water loss was completed in the Safford Valley of Arizona by the U. S. Geological Survey (Gatewood et al., 1950). By lysimeter studies it was shown that tamarisk had a higher water consumption than either seepwillow or cottonwood. Also, it was estimated that total water use by vegetation during the 12-month period ending September 30, 1944, was 28,000 acre-feet for the 9,303 acres of a 46-mile stretch of the Gila River. Of this amount 23,000 acre-feet was derived from the ground-water reservoirs and the remainder from precipitation. Tamarisk used 75 percent of the total. Similar high losses have been estimated for the Salt River (Turner and Skibitzke, 1952).

In New Mexico, Thompson (1957) estimated that more than 113,000 acres are infested with tamarisk in the lower valleys of the Rio Grande and Pecos Rivers. On a stretch of the Rio Grande, water loss has been estimated as 5.8 acre-feet per acre per year. On the same river, channelization through a heavy phreatophyte stand saved an estimated 45,000 acre-feet per year (Elliott, 1957). Fletcher and Elmendorf (1955) and Robinson (1958) point out that flood plain vegetation affects considerable water loss that possibly could be saved by manipulation of vegetation.

SURFACE FLOW

The U. S. Geological Survey began compiling records of streamflow from major streams in 1888. Work in the Colorado Basin started the next year.(U. S. Geological Survey, 1954). These records, where available, provide an excellent base for study of streamflow. Some of the difficulties of streamflow measurement in the Southwest where stream channels frequently carry debris-laden flood flows were outlined by Smith (1914) and Schwalen and Shaw (1957). Schwalen (1942) related rainfall to runoff in the Santa Cruz River watershed above Tucson and determined that for the period 1923-41 only 0.6 percent of rainfall resulted in runoff.

Leopold and Miller (1956) measured the hydraulic factors of width, depth, velocity, and suspended sediment load of ephemeral streams during flood flow near Santa Fe, New Mexico. These flood-flow data in conjunction with an analysis of drainage basin configuration, were used to determine the interrelation of stream order and hydraulic variables. Ford (1953) determined that most hydrologic phenomena are products of multiple causation. Flood season discharge, for example, is associated with several variables, antecedent in time, among which are accumulated precipitation, ground water conditions, and temperature.

Fletcher and Rich (1955), applying knowledge of evapo-transpiration in relation to precipitation as expressed by Thornthwaite (1948), classified the watersheds of the Southwest as to their streamflow and water yield characteristics. Cooperrider and Sykes (1938) outlined the relationships of streamflow to precipitation on the Salt River watershed above Roosevelt Dam later. Cooperrider et al. (1945) developed a relationship of streamflow and precipitation in Parker Creek to measured flow in the Salt River for use in predicting flow. Rowe and Colman (1951) analyzed the amounts of water that would be lost through interception, evapo-transpiration, and other processes on two California mountain areas. By subtracting these losses from the precipitation, they estimated the amount of water penetrating into the rock strata.

Hardaway (1956) using Santa Fe River data prepared a graph showing how a watershed functions, emphasizing that the storage capacity of a watershed must be filled before streamflow is yielded.

Goodell (1951) presents a method for comparing the flow from a pair of experimental watersheds. The annual streamflow of one experimental

watershed is predicted from that of the other. The watersheds are not similar in size or in topographical characteristics. But, they are at similar elevations.

Hickok et al. (1958) presents a method of hydrographic synthesis for use on small arid land watersheds. The method involves using an estimated watershed lag time to predict the hydrograph peak rate for a total volume of runoff and synthesizing the entire hydrograph using lag time, estimated peak rate, and a standard dimentionless hydrograph.

EROSION

Water from rain or melting snow that does not enter the soil must flow over the soil surface until it either penetrates into the ground or reaches a stream channel where flood flows may often cause gullying, especially in arid regions (Peterson, 1958). Vegetation exerts a significant influence upon stabilizing the soil and preventing erosion. During the 1930's many flood control surveys were undertaken to evaluate the effects and consequences of surface flow upon erosion and floods. The U. S. Department of Agriculture report on the Rio Puerco watershed (1941) is a good example. Such surveys emphasized the reduction of floods by the stabilization of soil. Cooperrider and Hendricks (1937) made a special study of soil erosion and streamflow on range and forest lands of the Upper Rio Grande watershed. More recently, Dortignac (1956b) summarized the watershed resource information for the Upper Rio Grande basin. He concluded that "soil out of place" is the greatest threat to the future of the basin. Brown (1945) stated that sediment is one of the major problems involved in utilization of the water resources of southwestern States. The enormous quantities of solid matter carried by many western streams has a significant and often deciding influence on the location, design, and maintenance of storage reservoirs. He presents data useful in estimating quantities of sediment carried by streams in the Colorado, Gila, Rio Grande, and Pecos River watersheds.

Destruction of cover was recognized as an important factor contributing to floods and erosion. Bryan (1925), from extensive observations of the valley arroyos in the arid Southwest, recognized the effect of overgrazing in triggering gullying action. Bailey (1935) felt that modification of the plant cover by overgrazing was probably the dominant cause of accelerated erosion. Thornthwaite et al. (1942) stated that careful management would go far toward controlling accelerated erosion. Leopold (1951), however, concluded that restoration of higher density vegetation over large areas of southwestern watersheds was questionable and that range protection alone could not restore these valleys to their original stability.

Talbot (1937) in outlining indicators of southwestern range conditions stated that "The use of erosion as a grazing indicator is full of chances for error. Any attempt to correlate present erosion with present grazing is especially difficult. Two generalizations will be found

helpful: (1) Distinct increase in number of recent gullies certainly indicates a 'slipping range,' and is frequently but not invariably one of the later stages of overgrazing; (2) failure of vegetation to reclaim very small gullies resulting from past abuse also is a hint that recuperation has not yet begun."

Johnson and Niederhof (1941) reporting results obtained from 1/200-acre plots on granitic soils in Colorado stated that runoff was greatest on the abandoned field, intermediate on the bunchgrass on alluvial soil, and least on the bunchgrass on residual soil. An increase in rainfall intensity from 2 to 4 inches per hour more than tripled the surface runoff for all types. Erosion was most rapid on the abandoned field, intermediate on the bunchgrass on residual soil, and least on the bunchgrass on alluvial soil. The total volume of eroded material increased with increased rainfall intensity. But the amount of material carried per cubic foot of runoff showed no significant change.

Dunford (1954) working in the pine grasslands of the Colorado Front Range reported that the average runoff before grazing from bunchgrass plots varied from 0.24 to 0.27 inch. In the 12 years after grazing, the heavily grazed plots yielded an average of 0.34 inch of runoff per season; moderately grazed, 0.22 inch; and nongrazed, 0.11 inch per season. Erosion from these same plots before grazing ranged from 111 pounds to 163 pounds per acre. After grazing the average annual deposition for seasons of occurrence were 134, 145, and 316 pounds per acre respectively for non-, moderate, and heavy grazing. On ponderosa pine runoff plots, removal of litter resulted in 7 times the runoff from the treated plot than from the untreated. After 7 years the runoff from the treated and untreated plots again became similar. Removal of both trees and litter resulted in 16 times more runoff from the treated plots than from the untreated. In both instances erosion following treatment amounted to nearly 4 tons per acre.

Rosa and Tigerman (1951) describe methods of relating sediment at stream gaging stations, reservoirs, and plots to broad classes of plant cover and soil conditions on both large and small drainage basins.

Fire in forest and brush types of the Southwest is known to increase erosion losses for several years. Soil losses up to 1.02 inches in depth occurred after an area burned on the Sierra Ancha Experimental Forest in Arizona (Hendricks and Johnson, 1944). Areas no larger than 30 foot, with deteriorated cover, were determined to be the source of destructive surface runoff and mud flows (Cooperrider and Hendricks, 1940). Near Northfork, California, an annually burned plot yielded 113 tons of soil per acre for a 9-year period; whereas check plot yielded only 12 pounds per acre (Rowe, 1948).

SOILS

Comparatively little work has been done on wild land soils in the Southwest. However, Retzer (1953) points out that, "Man's manipulation of site is limited to changes he can bring about in vegetation and soil. Since vegetation is dependent on soil for moisture and nutrients, then soil becomes the most important single factor that man can work with and change for better or worse. Soils have specific morphologic characteristics which form the basis of identification, enabling one to classify them much as plants are identified and classified. To be useful in land management, it is essential to know where the different soils are and how extensive each is in a particular area or region." He makes suggestions as to how field mapping should be carried out, techniques to be used, and classification of soil-vegetation groups to be employed.

Martin and Fletcher (1943) related the great soil groups of the United States found in vertical zones on Mt. Graham, Arizona, to the vegetation zones present on the mountain. They concluded that "the successive soil types representing climatic variation between that of the cold, highly humid forest and that of the hot, dry desert are in conformity with the system of great soil groups. Fletcher and Beutner (1941) studied the erodibility of the soils in the Upper Gila watershed.

WATERSHED IMPROVEMENT STUDIES

Vegetation plays an important role in watershed improvement. Osborn (1953, 1954a) points out that plant cover on the land surface offers resistance to the kinetic energy of rainstorms and protects the soil from detachment and dispersal by raindrop impact. The effectiveness of the cover in preventing soil splash is proportional to the amount present on the land at the time the rain falls. Osborn (1954b) also pointed out that soil splash on bare plots of rangeland revealed wide variations in the susceptibility of soils to movement by raindrop impact.

Renner and Love (1955) emphasize that the aim of management of water on western rangelands is one of getting the greatest amount of precipitation into the ground where it falls. They give examples on how this may be accomplished through management practices and through the use of mechanical measures.

One of the first major watershed improvement studies was that conducted on Watershed Areas A and B on the west slope of the Wasatch Plateau in central Utah. This study was begun in 1912. Forsling (1931) reports the findings up to and including 1929. Surface runoff and erosion from summer rains and melting snow from one watershed, when 16 percent of the surface was occupied by vegetation, are compared with runoff and erosion on the same area when the vegetation occupied 40 percent of the surface. The increase in the density of the vegetation from 16 to 40 percent reduced the rainfall surface runoff 64 percent, and rainfall erosion 54 percent. It reduced erosion from melted snow 57 percent but did not influence runoff from melted snow.

Considerable research was directed toward soil stabilization at the Sierra Ancha Experimental Forest in connection with the CCC Program. Reports from these studies included recommendations for better soil stabilization methods by planting suitable plant species (Hendricks, 1936b), methods of controlling gullies (Hendricks, 1936c), erosion control on roads (Hendricks and Johnson, 1939; Hendricks and Grabe, 1939), use of grass litter (Hendricks, 1942), and proper conservation of watering places (Hendricks, 1936a; Sykes, 1937).

Effect of kind of cover on soil stabilization has also been determined at Sierra Ancha Experimental Forest on a watershed basis. These desert grassland watersheds, established in 1926, average less than an acre in size. Annual water yields between 1932 and 1941 averaged 1.6 to 6.4 percent of the rainfall (62 percent of the runoff coming during the summer). Soil loss for this same period averaged 5,649 tons per square mile per year, with 83 percent of the total sediment production resulting from intense summer storms. Four of the nine watersheds were seeded in 1953 to Boer and Lehmann lovegrass after the native shrubs were grubbed out and spread over the area for a mulch. Successful establishment of these grasses reduced sediment yields to less than 60 tons per square mile per year, as compared to 1,220 to 6,100 tons per square mile per year for the untreated watersheds (unpublished manuscript).

Love (1958) listed the following major factors needed to maintain or foster good grassland watershed conditions for the Front Range in Colorado: (1) A cover of herbaceous vegetation consisting of a high percentage of bunchgrasses; (2) a large amount of litter covering the soil surface; (3) a small percentage of bare or exposed soil; and (4) high noncapillary porosity of surface soils consistent with soil profile characteristics.

Reid and Love (1951) set forth procedures for an analyses of range-watershed conditions on the Roosevelt National Forest in Colorado.

Gardner and Hubbell (1944), Hubbell and Gardner (1950) working at the Navajo Experiment Station in New Mexico, describe methods of water conservation by diversion of storm runoff from gullies and arroyos and by use of crescent dikes to retain rain where it falls. Flooding increased the grass density of field plots where no more than 1 inch of sediment was deposited. Rapid deposition of more than 5 inches of sediment greatly damaged all grasses except western wheatgrass. Forage production on lightly silted portions of flooded areas was 3 to 9 times that on comparable unflooded areas.

Craddock and Pearse (1938) through a series of infiltrometer tests on 30 and 40 percent slopes under disturbed and undisturbed conditions on granitic soils in Idaho concluded that wheatgrass range was superior to existing range types for controlling runoff and erosion. Arnold and Schroeder (1955) evaluated 7 sites where juniper was cleared

over a period of 13 years on the Fort Apache Reservation in eastern Arizona. Following control, ecologically superior plants tended to displace ecologically inferior plants. Areas that had been cleared for two growing seasons produced an average of 82 pounds of herbage per acre more than the areas cleared for one growing season. After 8 growing seasons, the average increase in herbage yield tapered off at a productive level of about 650 to 700 air-dry pounds per acre.

WATER YIELD STUDIES

Few studies of vegetation changes made primarily to increase water yield without regard for maximum production of wood, forage, and other values have been going long enough to reach publication stage. The first such study was started in 1910 by the Forest Service in cooperation with the Weather Bureau at Wagon Wheel Gap on the Upper Rio Grande in Colorado. As reported by Bates and Henry (1928) two contiguous watersheds, each slightly more than 200 acres in size, were selected between elevations of 9,000 and 10,000 feet. The watersheds were left in their natural cover of Douglas-fir, pine, spruce, and aspen for 8 years of calibration. One watershed was denuded in 1919 and permitted to regrow to a stand of aspen sprouts. In the 8 years of the pretreatment period, the watersheds averaged 6.08 and 6.18 inches of yearly runoff. After treatment, the denuded watershed yielded an average of 7.26 inches per year for a 7-year period, with the check watershed yielding 6.20 inches per year. This difference decreased as the vegetation regrew in the denuded watershed until it was about one-half inch in the sixth and seventh years. The excess discharge occurred almost entirely during the snowmelt period. During the 7 years of the study, the area originally denuded and allowed to grow back showed little evidence of increase of surface runoff and almost no erosion.

More recent studies elsewhere in Colorado tend to confirm results obtained at Wagon Wheel Gap. Love (1955) found that during 5 years following the killing of extensive stands of spruce by beetles, streamflow increased 22 percent in the White River. Preliminary findings following harvesting of 50 percent of the lodgepole pine and spruce and fir timber from Fool Creek at the Fraser Experimental Forest, Colorado, showed an increase in water yield of 37 percent in 1956 but only 17.5 percent in 1957 (Love, 1953; Goodell, 1958). Most of this increase in water yield occurred in the spring freshet. The spring flood peak of the logged watersheds increased the first year after cutting, but decreased in comparison with the control the second year. These variations in amount and distribution of streamflow from year to year indicate the need for caution in applying results until additional data are obtained. Caution is also needed when applying results obtained in Colorado to more arid and climatically different conditions such as in Arizona. For example, preliminary information from the Workman Creek watersheds at the Sierra Ancha Experimental Forest thus far indicate no change in total or seasonal water yield or diurnal discharge pattern from removal of broadleaf trees growing along the stream channel. Moreover, partial timber cutting thus

far has not produced measurable increases in water yield during the recent drought years. Additional years' records, particularly of above-average precipitation periods, may give other results (unpublished manuscript).

Four watersheds in mixed chaparral-grassland transition at the Sierra Ancha Experimental Forest, varying from 9 to 20 acres in size, were instrumented in 1934. After a calibration period, moderate grazing (40 percent utilization) was initiated on one watershed in 1939 and heavy grazing (80 percent utilization) on a second in 1942. Total water yields from all watersheds averaged between 5 and 10 percent of the precipitation (more than 85 percent of the annual water yield occurred during the winter). Grass density increased on the moderately grazed and on the check watersheds, but there was no statistical difference in water yields among the watersheds. Between 1953 and 1956 shrubs were poisoned on two of the four watersheds and perennial grass was seeded on the areas. A slight increase in streamflow was measured in 1957, the first year following treatment. Additional records are needed to determine whether treatment differences are significant (unpublished manuscript).

Goodell and Wilm (1955) outlined some general concepts of how to get more snow water from forest lands through timber harvesting. They describe several studies carried on at the Fraser Experimental Forest in Colorado and elsewhere in the United States. They point out that no research results are available yet to indicate what may be the best management for forested watersheds for both water production and wood products. Soil, topography, climate, and forest characteristics, all play a part and must be considered in plans designed to get maximum benefits from the forest and snowfields.

Recently some attention has been given to alpine snowfields -- snowfields above timber line -- and their importance to water yield. Martinelli (1957, 1958) points out that snowfields in the alpine zone of Colorado mountains are one of the major factors helping to sustain streamflow during the summer months. The larger semipermanent snowfields have depths of 20-25 feet in early July. Summer ablation (vertical shrinkage of snow pack) averages about 2 feet per week. This releases about 15 to 16 inches of water for streamflow each week. Under certain atmospheric conditions these snowfields receive added moisture from the air as the result of condensation; under other conditions moisture is lost from the fields by evaporation. However, in either case the absolute amount of moisture involved is less than 5 percent of the melt produced. Indications are that artificial barriers might increase the efficiency of natural snow catchments and increase the volume of snow retained at high elevations. Such an increase in the amount of snow retained in drifts at the higher elevations should be reflected as an increase in the streamflow during the late summer months.

RECENT EMPHASIS ON WATER YIELD STUDIES

Because of the need for additional water to sustain developments in the Southwest, attention has been focused on possibilities of increasing water yields. The Arizona State Land Department Water Division, the Salt River Valley Water Users' Association, and the University of Arizona cooperating made a survey study of the possibilities of increasing water yield from the Salt River watershed. A report titled "Recovering Rainfall" (Anderson et al., 1956) was published in two parts: Part I is the summary; Part II, under the same title, contains reports as prepared by several consultants.

Following release of this report a citizens' group was formed in December 1956 "to bring about wide participation of the public in the Watershed Program" (Arizona Watershed Program booklet). This group is known as the Arizona Water Resources Committee. Members and its subcommittees include 60 leading citizens representative of Arizona's economy. One of their two-pronged projects to improve water utilization and yield is "research -- to give encouragement to and seek funds for further and continued experiments in watershed management."

PRESENT WATER YIELD STUDIES IN ARIZONA

The present studies in Arizona pertaining to water yield have not been under way long enough for formal reporting of results. With the view that published results will begin to appear in the near future, brief descriptions of the studies now under way are here presented. For the most part, the studies will be outlined by vegetation type, beginning at the higher elevations on the mountain tops and working downward to the valley stream bottoms (Price and Hoover, 1957).

MIXED CONIFER TYPE

Watershed research in the mixed conifer type -- white fir, ponderosa pine, Douglas-fir, spruce and aspen -- is under way at the Workman Creek watersheds on the Sierra Ancha Experimental Forest and at Willow Creek on the Apache National Forest. Workman Creek watersheds vary from 248 to 511 acres in size and are located at about 6,500 feet elevation on a westerly aspect. The stream gaging stations and the rain gage network were established in 1938. After calibration, watershed treatments were started on two watersheds in 1953, with the third left untreated as a climatic control. The first treatment in the summer of 1953 of the North Fork watershed removed the deciduous riparian vegetation (about 0.6 percent of the total basal area of the watershed). No change in total or seasonal water yield, or diurnal discharge pattern resulted from removal of the riparian vegetation. The second treatment, in the fall of 1958, removed all of the pine-fir timber in the moist bottom site of 80 acres (about one-third of the watershed). The area is being converted to perennial

grass. On the South Fork watershed timber was logged in accordance with advanced National Forest timber harvesting practices. Approximately 50 percent of the merchantable timber was removed between 1953 and 1955. Information thus far indicates no measurable increase in water yield. However, as stated earlier, the years since treatment have been drought years. Results may change as more data are obtained and if years of above-average precipitation occur. This work is being done by the Forest Service with the Salt River Valley Water Users cooperating.

The work at Willow Creek is just beginning. Here two watersheds, 350 and 515 acres in size, are being calibrated for later timber harvesting treatment. On another watershed of 800 acres, demonstrations of timber harvesting are being applied. Supplementary studies include comparative moisture use by grass, spruce, and aspen; also reconnaissance measurements of water yields of vegetation types in relation to character and amount of precipitation, underlying geologic structure, and size and orientation of watersheds. The work is being done by the Forest Service with the Arizona State Game Department cooperating in the game habitat and wildlife phases.

PONDEROSA PINE-BUNCHGRASS TYPE

Ponderosa pine forests is the extensive forest type of the Coconino Plateau and adjoining areas. Watershed research and pilot tests conducted by the Forest Service are located at Castle Creek on the Apache National Forest, Beaver Creek on the Coconino National Forest, and at the Sierra Ancha Experimental Forest. Except for the ponderosa pine phases at the Workman Creek watersheds at Sierra Ancha, work in this type has been under way only a few years.

At Castle Creek two watersheds of about 1,000 acres each are under calibration preliminary to timber harvesting treatment. At Beaver Creek, which has a total area of 277,000 acres, there are six sub-watersheds varying in size from 300 to 2,000 acres in the ponderosa pine type undergoing calibration preliminary to treatment. Treatments will include various degrees of timber harvesting, including total removal of timber and conversion to grass, and use of fire. Two additional sub-watersheds are being used to demonstrate various timber harvesting methods. Supplemental studies of interception, infiltration, use of moisture, sedimentation, and erosion are under way. The Arizona State Game Department is cooperating in the game habitat and wildlife phases.

The U. S. Bureau of Indian Affairs, in cooperation with the Apache Tribal Council, is beginning a pilot watershed study on the Apache Reservation at Carrizo and Corduroy Creeks. The plan is that Carrizo Creek, an area of 166,000 acres, will be used as a climatic check. Corduroy Creek, an area of 146,000 acres, is to be used as a paired and treated watershed. Prescribed burning, livestock grazing, and pinyon-juniper control will be applied to the treated watershed. The U. S. Geological Survey is cooperating in gaging the streams.

PINYON-JUNIPER TYPE

The pinyon-juniper type is extensive in Arizona and New Mexico. Watershed research in this type is located at the Beaver Creek pilot watershed area. Here, three sub-watersheds in the Utah juniper type and three sub-watersheds in the alligator juniper type, varying in size from 150 to 400 acres, are undergoing calibration preliminary to treatment. Treatment will include several methods of pinyon-juniper control and seeding to grasses. Supplemental studies of soil moisture, interception, siltation, and erosion are included. The Forest Service is doing this work with the Arizona State Game Department cooperating in the game habitat and wildlife phases. The Agriculture Research Service is cooperating in the pinyon-juniper control phases. The U. S. Geological Survey constructed the two main gaging stations on Beaver Creek under contract with the Forest Service.

CHAPARRAL TYPE

The recent watershed research in the chaparral type with specific reference to water yield on a watershed basis has been under way just over a year. The studies are located at Whitespar and Mingus Mountain near Prescott and at Three-Bar near Roosevelt. A cluster of two to four watersheds, varying in size from 48 to 310 acres at each area, are under calibration preliminary to treatment. Treatment will include several methods of controlling and eradicating brush species including the use of chemicals and fire, and seeding of grasses. Supplemental studies of soil moisture and ecology, and physiology of the brush species are included.

The work is being done by the Forest Service with the Agricultural Research Service cooperating in the shrub control phases including use of chemicals, the Arizona State Game Department cooperating in the game habitat and wildlife phases, and the Salt River Valley Water Users' Association cooperating at the Three-Bar area.

SEMIDESERT

In the semidesert grass-mixed shrub type the Forest Service has studies of water yield at the Summit experimental watersheds midway between Globe and Roosevelt. Here, nine sub-watersheds 0.37 to 1.05 acres in size on soils derived from granite have been under protection since 1925 to follow the nature and rate of natural recovery. Recently the shrubs on three of the watersheds have been eradicated and the areas established with a perennial grass cover. Surface runoff and erosion on the "grass converted" watersheds are being compared with runoff and erosion on the natural brush covered watersheds.

The Agriculture Research Service and the Soil Conservation Service are measuring precipitation and water yields on several sub-watersheds near Safford and Tombstone. At Safford there are four sub-watersheds, 519 to

764 acres in size, in a shrub-grass type. At Tombstone there are five sub-watersheds established within a 60-square mile range area. It is planned to evaluate range management practices such as seeding, brush control, pitting, and stock water developments as they are related to runoff.

PHREATOPHYTE

Phreatophytes -- vegetation growing along watercourses and in wet places -- use large quantities of water each year. Representatives of several agencies, including the U. S. Department of Agriculture, U. S. Department of the Interior, U. S. Army, and the State of New Mexico, formed a Salt Cedar Interagency Task Force in 1951 to report upon the phreatophyte problems. A Phreatophyte Subcommittee was later formed in the Pacific Southwest Inter-Agency Committee to disseminate information and to better coordinate research programs.

The Forest Service started research on phreatophytes in 1955. This project is concentrated upon the measurement of evapo-transpiration loss of various plant species and associations. Ecological studies of tamarisk and related phreatophytes are under way to determine means of their control and replacement by species using less water. The Agricultural Research Service is working upon control of tamarisk in Arizona by the use of herbicides (Arle, 1957).

During the past year the U. S. Geological Survey, the Arizona State Land Department, and the Salt River Valley Water Users' Association began a cooperative study at Cottonwood Wash near Kingman. The general objective of the study is to determine the water use of riparian species in a desert shrub habitat. Riparian species along the water course under study include cottonwood, willow, *Baccharis*, and sycamores. The experimental design is of the inflow-outflow type. Two reaches of stream about 1 mile in length are separated by gaging stations. Instrumentation includes three cement flumes and three ground water wells equipped with water level recorders. After a suitable period of calibration, riparian vegetation will be removed along one stretch of stream as a treatment.

Although not directly tied to water yield, the University of Arizona has a number of research projects under way that relate to watershed problems. These include ecological analyses of vegetation on specific sites, control of noxious plants, seeding, transpiration of shrubs and grasses, and treatment of the surface of small watershed areas for collection of runoff waters.

SUMMARY

People living in the arid Southwest have always been water conscious. Hence, over the many years of settlement numerous observations have been made concerning streamflow and water use. But, few have been recorded.

The first water was diverted from the Salt River in 1869 by settlers. Attention was also given to the need for watershed protection. This was one of the main purposes in establishing the Tonto National Forest in central Arizona in 1904.

Watershed management research had its start with the observations made by early workers in forestry and range management research. The first field work began June 1, 1910, at Wagon Wheel Gap, Colorado. Until recent years watershed research has been limited and sporadic. Also, most of the early research was designed to evaluate the protective value of forests and rangelands against soil erosion and floods. However, much useful information has been reported. The findings are classified and presented under three categories, namely: (1) Hydrologic processes; (2) watershed improvement studies; and (3) water yield studies.

Recently emphasis has been placed on studies and pilot watershed tests aimed at determining possibilities of increasing water yields. Watershed research has been quickened along this line, especially in Arizona. Studies are now under way in all major vegetation types from the top of the mountains to the stream channels in the valleys. Some pilot watershed tests also are in operation.

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LITERATURE CITED

Anderson, Carl A., Arnold, Joseph F., Barr, George W., and others.
1956. Recovering Rainfall. Arizona Watershed Program. Ariz. State Land Dept., Salt River Valley Water Users' Assoc., and Ariz. Univ. Part I, 1-33, illus., Part II, 1-218, illus.

Anderson, H. W.
1956. Forest-cover Effects on Snowpack Accumulation and Melt, Central Sierra Snow Laboratory. Amer. Geophys. Union Trans. 37: 307-312, illus.

Anderson, W. E., and White, B. D.
1953. Summary of Snow Surveys in Arizona, 1938 through 1953. U. S. Soil Conserv. Serv. Fed.-State Coop. Snow Surveys. 39 pp. [Processed.]

Antevs, Ernst.
1938. Rainfall and Tree Growth in the Great Basin. Amer. Geog. Soc. Spec. Pub. 21. 97 pp., illus.

Arle, H. Fred.
1957. Symposium on Phreatophytes: A Summary of Results of Experiments and Field Trials Pertaining to the Control of Salt Cedar (Tamarix gallica). Presented at Amer. Geophys. Union Pacific Southwest Region Mtg.,Sacramento, Calif., February 1957. Phreatophyte Subcom. of Pacific Southwest Interagency Com. 46-52. (Abstract in Amer. Geophys. Union Trans. 38: 414-415.)

Arnold, Joseph F., and Schroeder, W. L.
1955. Juniper Control Increases Forage Production on the Fort Apache Indian Reservation. U. S. Forest Serv. Rocky Mountain Forest and Range Expt. Sta. Sta. Paper 18, 35 pp., illus. [Processed.]

Bailey, Reed W.
1935. Epicycles of Erosion in the Valleys of the Colorado Plateau Province. Jour. Geol. 43: 337-355, illus.

Bates, Carlos G.
1923. Physiological Requirements of Rocky Mountain Trees. Jour. Agr. Res. 24: 97-164, illus.

______
1924. Forest Types in the Central Rocky Mountains as Affected by Climate and Soil. U. S. Dept. Agr. Bul. 1233, 152 pp., illus.

_______ and Henry, A. J.
1922. Stream-flow Experiment at Wagon Wheel Gap, Colo. Preliminary Report on Termination of First Stage of Experiment. U. S. Monthly Weather Rev. Sup. 17, 55 pp., illus.

_______ and Henry, A. J.
1928. Forest and Stream-flow Experiment at Wagon Wheel Gap, Colo. Final Report on Completion of the Second Phase of the Experiment. U. S. Monthly Weather Rev. Sup. 30, 79 pp., illus.

Beadle, B. W.
1956. Water Conservation through Control of Evaporation. N. Mex. Water Conf. Proc. 1956: 46-56. (N. Mex. Agr. Col., State College, N.Mex., Oct. 31, Nov. 1-2.) [Processed.]

Blaney, Harry F.
1958. Consumptive Water Requirements of Vegetative Cover in River Basins. Amer. Geophys. Union Trans. 39:____. (Presented at 39th annual meeting; Trans. not yet published.)

Brown, Carl B.
1945. Rates of Sediment Production in Southwestern United States. U. S. Soil.Conserv. Serv. SCS-TP-58. 41 pp., illus. [Processed.]

Brown, H. E., and Dunford, E. G.
1956. Streamflow in Relation to Extent of Snow Cover in Central Colorado. U. S. Forest Serv. Rocky Mountain Forest and Range Expt. Sta. Sta. Paper 24, 9 pp., illus. [Processed.]

Bryan, Kirk.
1925. Date of Channel Trenching (Arroyo Cutting) in the Arid Southwest. Sci. 62: 338-344.

Bryson, R. A.
1957. The Annual March of Precipitation in Arizona, New Mexico, and Northwestern Mexico. Ariz. Univ. Atmos. Phys. Inst. Rpt. 6, 24 pp. [Processed.]

Cable, Dwight R.
1958. Estimating Surface Area of Ponderosa Pine Foliage in Central Arizona. Forest Sci. 4: 45-49, illus.

Colman, E. A.
1953. Vegetation and Watershed Management; An Appraisal of Vegetation Management in Relation to Water Supply, Flood Control, and Soil Erosion. 412 pp., illus. New York.

_______ and Hamilton, E. L.
1947. The San Dimas Lysimeters. U. S. Forest Serv. Calif. Forest and Range Expt. Sta. Res. Note 47, 33 pp., illus. [Processed.]

Cooperrider, C. K., Cassidy, H. O., and Niederhof, C. H.
1945. Forecasting Stream-flow of the Salt River, Arizona. Amer. Geophys. Union Trans. 26: 275-282, illus.

_______ and Hendricks, Barnard A.
1937. Soil Erosion and Stream Flow on Range and Forest Lands of the Upper Rio Grande Watershed in Relation to Land Resources and Human Welfare. U. S. Dept. Agr. Tech. Bul. 567, 88 pp., illus.

_______ and Hendricks, Barnard A.
1940. The Role of Vegetation on Steep Mountain Slopes. U. S. Forest Serv. Southwest. Forest and Range Expt. Sta. Res. Note 85, 3 pp. [Processed.]

_______ and Sykes, Glenton G.
1938. The Relationship of Stream Flow to Precipitation on the Salt River Watershed above Roosevelt Dam. Ariz. Agr. Expt. Sta. Tech. Bul. 76, 69 pp., illus. [Processed.]

Craddock, George W., and Pearse, C. Kenneth.
1938. Surface Run-off and Erosion on Granitic Mountain Soils of Idaho as Influenced by Range Cover, Soil Disturbance, Slope, and Precipitation Intensity. U. S. Dept. Agr. Cir. 482, 24 pp., illus.

Decker, John P., and Wein, Janet D.
1957. Symposium on Phreatophytes: An Infrared Apparatus for Measurement of Transpiration. Presented at Amer. Geophys. Union Pacific Southwest Region Mtg., Sacramento, Calif., February 1957. Phreatophyte Subcom. of Pacific Southwest Interagency Com. 32-41. (Abstract in Amer. Geophys. Union Trans. 38: 416, entitled "Time Course Studies of Transpiration of Tamarisk and Eucalyptus.")

_______ and Wetzel, Barton F.
1957. A Method for Measuring Transpiration of Intact Plants under Controlled Light, Humidity, and Temperature. Forest Sci. 3: 350-354, illus.

Dorroh, J. H., Jr.
1946. Certain Hydrologic and Climatic Characteristics of the Southwest. N. Mex. Univ. Press Engin. Pub. 1, 64 pp., illus.

Dortignac, E. J.
1951. Design and Operation of Rocky Mountain Infiltrometer. U. S. Forest Serv. Rocky Mountain Forest and Range Expt. Sta. Sta. Paper 5, 68 pp., illus. [Processed.]

_______ 1956a. Water Yields through Watershed Management. N. Mex. Water Conf. Proc. 1956:69-97. (N. Mex. Agr. Col., State College, N.Mex., Oct. 31, Nov. 1-2.) [Processed.]

_______ 1956b. Watershed Resources and Problems of the Upper Rio Grande Basin. U. S. Forest Serv. Rocky Mountain Forest and Range Expt.Sta. 107 pp., illus. [Processed.]

_______ 1958. Relation of Plant Cover to Infiltration and Erosion in Ponderosa Pine Forests of Colorado. Presented at 51st Amer. Soc. Agr. Engin. Ann. Mtg., Santa Barbara, Calif., June 1958. Paper 58-155, 16 pp., illus. [Processed.]

Dunford, E. G.
1954. Surface Runoff and Erosion from Pine Grasslands of the Colorado Front Range. Jour. Forestry 52: 923-927, illus.

_______ and Niederhof, C. H.
1944. Influence of Aspen, Young Lodgepole Pine, and Open Grassland Types upon Factors Affecting Water Yield. Jour. Forestry 42: 673-677, illus.

Elliott, E. W.
1957. Symposium on the Problems of the Upper Rio Grande, an Arid Zone River: Salt Cedar Control and Channelization in the San Marcial Area of the Middle Rio Grande in New Mexico. U. S. Commission for Arid Resource Impr. and Devlpmt. Pub. 1: 33-35.

Fletcher, Herbert C., and Elmendorf, Harold B.
1955. Phreatophytes--A Serious Problem in the West. U. S. Dept. Agr. Yearbook 1955: 423-429.

_______ and Rich, L. R.
1955. Classifying Southwestern Watersheds on the Basis of Water Yields. Jour. Forestry 53: 196-202, illus.

Fletcher, Joel E., and Beutner, E. L.
1941. Erodibility Investigations on Some Soils of the Upper Gila Watershed. U. S. Dept. Agr. Tech. Bul. 794, 32 pp., illus.

Ford, Perry M.
1953. Multiple Correlation in Forecasting Seasonal Runoff. U. S. Bur. Reclam. Engin. Monog. 2, 38 pp., illus. [Processed.]

Forsling, C. L.
1931. A Study of the Influence of Herbaceous Plant Cover on Surface Run-off and Soil Erosion in Relation to Grazing on the Wasatch Plateau in Utah. U. S. Dept. Agr. Tech. Bul. 220, 72 pp., illus.

Gardner, J. L., and Hubbell, D. S.
1944. Conservation of Runoff for Crop and Forage Production. U. S. Soil Conserv. Serv. Region 6 Bul. 94, 20 pp. [Processed.]

Garstka, W. U., Love, L. D., Goodell, B. C., and Bertle, F. A.
1958. Factors Affecting Snowmelt and Streamflow. A Report on the 1946-53 Cooperative Snow Investigations at the Fraser Experimental Forest, Fraser, Colorado. U. S. Bur. Reclam. and U. S. Forest Serv. Rocky Mountain Forest and Range Expt. Sta. 190 pp., illus.

Gatewood, J. S. , Robinson, T. W., Colby, B. R., and others.
1950. Use of Water by Bottom-land Vegetation in Lower Safford Valley, Arizona. U. S. Geol. Survey Water-Supply Paper 1103, 210 pp., illus.

Goodell, B. C.
1951. A Method for Comparing the Flow from a Pair of Experimental Watersheds. Amer. Geophys. Union Trans. 32: 927-930, illus.

____
1952. Watershed-management Aspects of Thinned Young Lodgepole Pine Stands. Jour. Forestry 50: 374-378, illus.

____
1958. A Preliminary Report on the First Year's Effects of Timber Harvesting on Water Yield from a Colorado Watershed. U. S. Forest Serv. Rocky Mountain Forest and Range Expt. Sta. Sta. Paper 36, 12 pp., illus. [Processed.]

_______ and Wilm, H. G.
1955. How to Get More Snow Water from Forest Lands. U. S. Dept. Agr. Yearbook 1955: 228-234.

Hamilton, E. L.
1954. Rainfall Sampling on Rugged Terrain. U. S. Dept. Agr. Tech. Bul. 1096, 41 pp., illus.

_______ and Rowe, P. B.
1949. Rainfall Interception by Chaparral in California. Calif. Dept. Nat. Resources, Div. Forestry. 43 pp., illus.

Hardaway, George D.
1956. Water Production from Forest Lands of New Mexico. Water Resources and their Economic Importance in New Mexico. N. Mex. Agr. Col. Agr. Econ. Dept. Spec. Rpt. 1: 47-51, illus.

Harrold, L. L.
1943. Thunder-storms and Runoff at High Elevations in Northwestern New Mexico. Amer. Geophys. Union Trans. 24: 425-438, illus.

Hendricks, Barnard A.
1936a. The Conservation of Water of Small Seeps, Springs, and Earth Tanks in the Southwest. U. S. Forest Serv. Southwest. Forest and Range Expt. Sta. Res. Note 3, 9 pp., illus. [Processed.] [Revised 1938.]

_______ 1936b. Revegetation of Small Gullies through the Use of Seeded Earth-filled Sacks. U. S. Forest Serv. Southwest. Forest and Range Expt. Sta. Res. Note 1, 3 pp., illus. [Processed.]

_______ 1936c. Vine-mesquite for Erosion Control on Southwestern Ranges. U. S. Dept. Agr. Leaflet 114, 8 pp., illus.

_______ 1942. Effect of Grass Litter on Infiltration of Rainfall on Granitic Soils in a Semidesert Shrub Grass Area. U. S. Forest Serv. Southwest. Forest and Range Expt. Sta. Res. Note 96, 3 pp. [Processed.]

_______ and Grabe, Neil.
1939. The Use of Cotton Netting in Revegetation of Road-fill Slopes. U. S. Forest Serv. Southwest. Forest and Range Expt. Sta. Res. Note 78, 4 pp., illus. [Processed.]

_______ and Johnson, Jerry.
1939. The Use of Brush Mats in Road-erosion Control. U. S. Forest Serv. Southwest. Forest and Range Expt. Sta. Res. Note 71, 2 pp. [Processed.]

______ and Johnson, Jerry M.
1944. Effects of Fire on Steep Mountain Slopes in Central Arizona. Jour. Forestry 42: 568-571, illus.

Hickok, R. B., Keppel, R. V., and Rafferty, B. R.
1958. Use of Watershed Characteristics in Hydrograph Synthesis for Small Arid Land Watersheds. Presented at 51st Amer. Soc. Agr. Engin. Ann. Mtg., Santa Barbara, Calif., June 1958. 10 pp., illus. [Processed.]

Horgan, Paul.
1954. Great River. The Rio Grande in North American History. 2 v., illus. New York, Toronto.

Hubbell, D. S., and Gardner, J. L.
1950. Effects of Diverting Sediment-laden Runoff from Arroyos to Range and Crop Lands. U. S. Dept. Agr. Tech. Bul. 1012, 83 pp., illus.

Hunter, Bryon, Cockerill, P. W., and Pingrey, H. B.
1939. Type of Farming and Ranching Areas in New Mexico. Part I. N. Mex. Agr. Expt. Sta. Bul. 261, 68 pp., illus.

Jaenicke, A. J., and Foerster, M. H.
1915. The Influence of a Western Yellow Pine Forest on the Accumulation and Melting of Snow. U. S. Monthly Weather Rev. 43: 115-126, illus.

Johnson, Wallace M.
1938. Infiltration and Capillary Rise in Sandy Soils. Minn. Acad. Sci. Proc. 6: 44-51.

______
1942. The Interception of Rain and Snow by a Forest of Young Ponderosa-pine. Amer. Geophys. Union Trans. 23: 566-570.

______ and Niederhof, C. H.
1941. Some Relationships of Plant Cover to Run-off Erosion, and Infiltration on Granitic Soils. Jour. Forestry 39: 854-858, illus.

Kassander, A. Richard, Jr.
1957. Research activities of the Institute of Atmospheric Physics as Related to the Arizona Watershed Program. Ariz. Watershed Program Proc. 1957: 34-37, App. 1-8. [Processed.]

Kittredge, Joseph.
1953. Influences of Forests on Snow in the Ponderosa - Sugar Pine - Fir Zone of the Central Sierra Nevada. Hilgardia 22: 1-96, illus.

Lassen, Leon, Lull, Howard W., and Frank, Bernard.
1952. Some Plant-soil-water Relations in Watershed Management. U. S. Dept. Agr. Cir. 910, 64 pp., illus.

Leopold, Luna B.
1942. Areal Extent of Intense Rainfalls, New Mexico and Arizona. Amer. Geophys. Union Trans. 23: 558-566, illus.

______ 1944. Characteristics of Heavy Rainfall in New Mexico and Arizona. Amer. Soc. Civ. Engin. Trans. 109: 837-892.

______ 1951. Vegetation of Southwestern Watersheds in the 19th Century. Geog. Rev. 41: 295-316, illus.

______ and Miller, John P.
1956. Ephemeral Streams -- Hydraulic Factors and their Relation to the Drainage Net. U. S. Geol. Survey Prof. Paper 282-A, 37 pp., illus.

Little, Elbert L., Jr.
1950. Southwestern Trees. A Guide to the Native Species of New Mexico and Arizona. U. S. Dept. Agr. Agr. Handb. 9, 109 pp., illus.

Love, L. Dudley.
1934. The Osmotic Values of Certain Native Forage Plants under Different Climatic and Soil Conditions in Southern Arizona. Ariz. Univ. Ph.D Thesis, 72 pp., illus. [Typewritten.]

______ 1953. Watershed Management in the Colorado Rockies. Jour. Soil and Water Conserv. 8: 107-112, illus.

______ 1955. The Effect on Stream Flow of the Killing of Spruce and Pine by the Engelmann Spruce Beetle. Amer. Geophys. Union Trans. 36: 113-118, illus.

______ 1958. Rangeland Watershed Management. Soc. Amer. Foresters Proc. 1958: ____. (Presented at annual meeting; Proc. not yet published.)

McDonald, J. E.
1956. Variability of Precipitation in an Arid Region. A Survey of Characteristics for Arizona. Ariz. Univ. Atmos. Phys. Inst. Rpt. 1, 88 pp. [Processed.]

McGinnies, W. G.
1952. A Report on the Ecology of the Arid and Semi-arid Areas of the United States and Canada Prepared for UNESCO. United Nations Ed., Sci., and Cult. Organ. Arid Zone Programme. Paris. 6 October 1952. 69 pp. text, 43 pp. biblio. [Processed.]

_______ and Arnold, Joseph F.
1939. Relative Water Requirement of Arizona Range Plants. Ariz. Agr. Expt. Sta. Tech. Bul. 80, 246 pp., illus. [Processed.]

Martin, W. P., and Fletcher, Joel E.
1943. Vertical Zonation of Great Soil Groups on Mt.Graham, Arizona, as Correlated with Climate, Vegetation, and Profile Characteristics. Ariz. Univ. Tech. Bul. 99, 153 pp., illus.

_______ and Rich, L. R.
1948. Preliminary Hydrologic Results, 1935-48, "Base Rock" Undisturbed Soil Lysimeters in the Grassland Type, Arizona. Soil Sci. Soc. Amer. Proc. 13: 561-567, illus.

Martinelli, Mario, Jr.
1957. Hydrology of Alpine Snowfields. N.Y. State Col. Forestry, Syracuse, Ph.D. Thesis. 160 pp., illus. [Typewritten.]

____
1958. Some Hydrologic Aspects of Alpine Snowfields under Summer Conditions. Amer. Geophys. Union Trans. 39:_____. (Presented at 39th annual meeting; Trans. not yet published.)

Miller, David H.
1956. The Influence of Pine Forest on Daytime Temperature in the Sierra Nevada. Geog. Rev. 46: 209-218, illus.

Nichol, A. A.
1937. The Natural Vegetation of Arizona. Ariz. Agr. Expt. Sta. Tech. Bul. 68: 181-222, illus.

Osborn, Ben.
1953. Field Measurements of Soil Splash to Evaluate Ground Cover. Jour. Soil and Water Conserv. 8: 255-260, 266, illus.

____
1954a. Effectiveness of Cover in Reducing Soil Splash by Raindrop Impact. Jour. Soil and Water Conserv. 9: 70-76, illus.

____
1954b. Soil Splash by Raindrop Impact on Bare Soils. Jour. Soil and Water Conserv. 9: 33-38, 43, 49, illus.

Packer, Paul E.
1951. An Approach to Watershed Protection Criteria. Jour. Forestry 49: 639-644, illus.

Pearson, G. A.
1931. Forest Types in the Southwest as Determined by Climate and Soil. U. S. Dept. Agr. Tech. Bul. 247, 144 pp., illus.

Peterson, H. V.
1958. Erosion and Sediment Problems on Western Arid Lands. Amer. Geophys. Union Trans. 39:_____. (Presented at 39th annual meeting; Trans. not yet published.)

Price, Raymond, and Hoover, Marvin D.
1957. Watershed Management Research in Arizona Conducted by the Forest Service. Ariz. Watershed Program Proc. 1957: 5-10, illus. [Processed.]

Reid, Elbert H., and Love, L. D.
1951. Range-watershed Conditions and Recommendations for Management, Elk Ridge and Lower Elk Ridge Cattle Allotments, Roosevelt National Forest, Colorado. U. S. Forest Serv. 123 pp., illus. [Processed.]

Reitan, C. H.
1957. The Role of Precipitable Water Vapor in Arizona's Summer Rains. Ariz. Univ. Atmos. Phys. Inst. Rpt. 2, 18 pp. [Processed.]

Renner, F. G., and Love, L. D.
1955. Management of Water on Western Rangelands. U. S. Dept. Agr. Yearbook 1955: 415-423.

Retzer, John L.
1953. Soil-vegetation Surveys of Wildlands. Jour. Forestry 51: 615-619, illus.

Rich, L. R.
1952. Symposium -- Consumptive Use of Water: Forest and Range Vegetation. Amer. Soc. Civ. Engin. Trans. 117: 974-990, illus.

Robinson, T. W.
1958. Phreatophytes. U. S. Geol. Survey Water-Supply Paper 1423, 84 pp., illus.

Roeser, Jacob, Jr.
1940. The Water Requirement of Rocky Mountain Conifers. Jour. Forestry 38: 24-26.

Rosa, J. M., and Tigerman, M. H.
1951. Some Methods for Relating Sediment Production to Watershed Conditions. U. S. Forest Serv. Intermountain Forest and Range Expt. Sta. Res. Paper 26, 19 pp., illus. [Processed.]

Rowe, P. B.
1940. The Construction, Operation, and Use of the North Fork Infiltrometer. Flood Control Coordinating Com. Misc. Pub. 1 and U. S. Forest Serv. Calif. Forest and Range Expt. Sta. Misc. Pub. 1, 64 pp., illus.

______ 1948. Influence of Woodland Chaparral on Water and Soil in Central California. Calif. Dept. Nat. Resources, Div. Forestry. 70 pp., illus.

______ 1955. Effects of the Forest Floor on Disposition of Rainfall in Pine Stands. Jour. Forestry 53: 342-348, illus.

______ and Colman, E. A.
1951. Disposition of Rainfall in Two Mountain Areas of California. U. S. Dept. Agr. Tech. Bul. 1048, 84 pp., illus.

______ and Hendrix, T. M.
1951. Interception of Rain and Snow by Second-growth Ponderosa Pine. Amer. Geophys. Union Trans. 32: 903-908, illus.

Russler, Ben H., and Spreen, William C.
1947. Topographically Adjusted Normal Isohyetal Maps for Western Colorado. U. S. Weather Bur. Tech. Paper 4, 27 pp., illus.

Salt Cedar Interagency Task Force.
1951. Report to Salt Cedar Interagency Council, Albuquerque, New Mexico. 29 pp., 6 app., illus. [Processed.]

Salt River Project Agricultural Improvement and Power District and Salt River Valley Water Users' Association.
1954. Salt River Project, Major Facts in Brief. 28 pp., illus. [Processed.]

Schulman, Edmund.
1945. Tree-ring Hydrology of the Colorado River Basin. Ariz. Univ. Lab. Tree Ring Res. Bul. 2, 51 pp., illus.

______ 1946. Dendrochronology at Mesa Verde National Park. Tree-Ring Bul. 12: 18-24.

______ 1948. Dendrochronology at Navajo National Monument. Tree-Ring Bul. 14: 18-24.

______ 1949. Early Chronologies in the San Juan Basin. Tree-Ring Bul. 15: 24-32.

Schwalen, Harold C.
1942. Rainfall and Runoff in the Upper Santa Cruz River Drainage Basin. Ariz. Agr. Expt. Sta. Tech. Bul. 95: 421-472, illus.

______ ahd Shaw, R. J.
1957. Ground Water Supplies of Santa Cruz Valley of Southern Arizona between Rillito Station and the International Boundary. Ariz. Agr. Expt. Sta. Bul. 288, 119 pp., illus.

Shantz, H. L.
1948. Water Economy of Plants. Santa Barbara Bot. Gard. Leaflet 1(6), 54 pp., illus. [Calif.]

Smith, G. E. P.
1914. Discussion of "Measurement of the Flow of Stream by Approved Weirs with New Formulas and Diagrams: Details and Summaries of the Results of Experiments by Francis, Bazin, Fteley, and Stearns, and at the Hydraulic Laboratories of Cornell University and the University of Utah," by Richard R. Lyman. Amer. Soc. Civ. Engin. Trans. 77: 1300-1303.

Smith, Hillard L., and Leopold, Luna B.
1942. Infiltration Studies in the Pecos River Watershed, New Mexico and Texas. Soil Sci. 53: 195-204, illus.

Smith, H. V.
1956. The Climate of Arizona. Ariz. Agr. Expt. Sta. Bul. 279, 99 pp., illus.

Sykes, Glenton G.
1937. Desert Water Tanks. U. S. Forest Serv. Southwest. Forest and Range Expt. Sta. Res. Note 18, 2 pp. [Processed.]

Talbot, M. W.
1937. Indicators of Southwestern Range Conditions. U. S. Dept. Agr. Farmers' Bul. 1782, 35 pp., illus. (Slightly revised, 1957.)

Taylor, Colin A., and Nickle, Harry G.
1933. Water Losses under Natural Conditions from Wet Areas in Southern California. Chapter IV. Investigations in Coldwater Canyon. Calif. Dept. Pub. Works, Div. Water Resources Bul. 44: 88-121, illus.

Thompson, C. B.
1957. Importance of Phreatophytes in Water Supply. N. Mex. State Engin. Off. 16 pp. [Processed.]

Thornthwaite, C. W.
1948. An Approach Toward a Rational Classification of Climate. Geog. Rev. 38: 55-94, illus.

_______, Sharpe, C. F. Stewart, and Dosch, Earl F.
1942. Climate and Accelerated Erosion in the Arid and Semiarid Southwest, with Special Reference to the Polacca Wash Drainage Basin, Arizona. U. S. Dept. Agr. Tech. Bul. 808, 134 pp., illus.

Turner, George T., and Dortignac, Edward J.
1954. Infiltration, Erosion, and Herbage Production of Some Mountain Grasslands in Western Colorado. Jour. Forestry 52: 858-860.

Turner, S. F., and Skibitzke, H. E.
1952. Use of Water by Phreatophytes in 2000-foot Channel Between Granite Reef and Gillespie Dams, Maricopa County, Arizona. Amer. Geophys. Union Trans. 33: 66-72, illus.

U. S. Department of Agriculture.
1941. Rio Puerco Watershed Flood Control Survey Report, New Mexico. (Revised.) 584 pp. Part II, Appendix, Supplementary Information, 201 pp., illus. [Processed.]

U. S. Forest Service, Southwestern Forest and Range Experiment Station.
1953. The Sierra Ancha Experimental Watersheds. 32 pp., illus. [Processed.]

U. S. Geological Survey.
1954. Compilation of Records of Surface Waters of the United States through September 1950. Part 9. Colorado River Basin. U. S. Geol. Survey Water-Supply Paper 1313, 749 pp., illus.

Wilm, H. G.
1946. The Design and Analysis of Methods for Sampling Microclimatic Factors. Amer. Statis. Assoc. Jour. 41: 221-232.

_______ and Dunford, E. G.
1948. Effect of Timber Cutting on Water Available for Stream Flow from a Lodgepole Pine Forest. U. S. Dept. Agr. Tech. Bul. 968, 43 pp., illus.

Woodward, Lowell.
1943. Infiltration-capacities of some Plant-soil Complexes on Utah Range Watershed-lands. Amer. Geophys. Union Trans. 24: 468-475, illus.

Zon, R.
1912. Forests and Water in the Light of Scientific Investigation. pp. 205-302. (U. S. Congress 62d, 2d Sess., Senate Doc. 469.) (Reprinted 1927.)

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